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Physics Procedia 39 (2012) 318 – 326

Physics Procedia

LANE 2012

Improved Formability of Aluminum Alloys using Laser induced Hardening of Tailored Heat Treated Blanks

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Abstract

Tailored Heat Treated Blanks can considerably enhance the formability of fast-hardenable aluminum alloys, e.g. for car body parts. These blanks exhibit a properties distribution over the sheet plane, which is optimized for the forming operation. In this paper, the enhancement of the material strength of fast-hardenable aluminum alloys with a laser is in focus. Hereby, the working principle of the hardening is presented. Moreover, a process window for the hardening process is elaborated identifying the temperature and holding time as key parameters. Furthermore, heat treatment layouts are considered demonstrating the impact of hardening on the improvement of forming limit of fast-hardenable aluminum alloys.

Keywords: Laser radiation; Tailored Heat Treated Blanks; Layout design; Forming limit; Laser hardening

1. Introduction

Climate warming, cumulative CO_2-emissions, increasing oil prices and environmental awareness have prompted a rethinking in the automotive industry [1]. Lightweight construction has become and will remain indispensable to car manufacture for two main reasons: on the one hand, to meet CO_2-emission targets and to reduce fuel consumption, on the other hand to enhance the driving comfort and safety of future cars [2]. Regarding lightweight car body parts, aluminum alloys offer, due to their good strength/weight ratio, great potential for weight reduction. The high specific strength, stiffness and the corrosion resistance have promoted a broad field of applications for aluminum alloys. Compared to deep drawing steels, like DC04, the formability of aluminum alloys, however, is low. Several innovative tech-

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 doi:10.1016/j.phpro.2012.10.044

nologies have been considered to improve the forming limits of aluminum alloys. One of the main research topics at the Chair of Manufacturing Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, focuses on so-called Tailored Heat-treated Blanks (THTB). These blanks are locally heat treated blanks with a specific strength distribution. In order to enhance the forming limit of aluminum blanks, the idea of THTB is to adapt the material characteristics to the forming operation like deep drawing. The material properties can be modified by a local heat treatment. Due to the optimized properties distribution, the material flow from the forming zone into critical blank areas can be improved significantly, to enhance the forming limit of the material. This paper deals with the principles and application of hardening, to improve of the forming limit of fast-hardenable aluminum alloys.

2. Working mechanism of local hardening

Tailored Heat Treated Blanks represent one promising possibility to improve the formability of aluminum alloys close to series production. In order to achieve an enhancement of the forming limits by the application of THTB, a fundamental understanding and working principles of this technology have to be built up. In the following, the working mechanism of local hardening is presented (Fig. 1).

The first mechanism of the local hardening represents the prevention of wrinkling. Because of the upcoming compression stresses during the forming operation, instabilities appear in the sheet metal leading to buckling of the sheet out of the sheet plane. This phenomenon occurs in the wall zone between bottom and flange, where the blank has no tool contact, or in the flange zone representing the forming zone of the deep drawing part. In the flange zone, the buckling rises up because of the tension/compression stresses. The so-called wrinkles of the first order can be suppressed increasing the blank holder pressure. In the wall zone with no tool contact, the puckers can be avoided by increasing the yielding point. The local hardening, hereby, results in a higher resistance against the upcoming tangential compression stresses, which cause the buckling of the second order, and a later plastification of the metal. Due to the delayed material plastification, finally, the process limit of the forming operation can be shifted to higher forming ratio and therefore the risk of failure by wrinkling be delayed (Fig. 1).

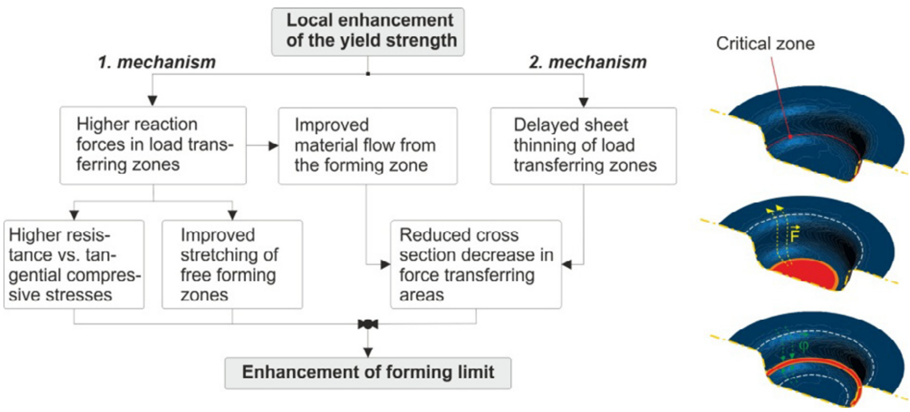

Fig. 1. Working principles of local hardening of Tailored Heat Treated Blanks

The second mechanism of this approach is to limit the cross section reduction in the force-transferring zones leading to a higher formability of the aluminum alloy. Above all, the transitional zone between bottom and wall showing a plane strain deformation is at risk of cracks. A local hardening of this transitional zone would first delay an early plastification and therefore a local thinning of the material. Due to the enhanced resistance against yielding in thickness direction, the material can sustain higher stresses and the formability of the material increases. Second, the local hardening itself promotes to a better force transfer and thereby benefits the material flow from the forming into critical zones. This effect results in the increased formability of the aluminum alloy.

Besides the working mechanisms, the local hardening of THTB and its influence on the strength distribution of the material is essential for the forming behavior. In dependency of its use on the sheet metal, different effects are advantageous or disadvantageous for the aimed enhanced forming limit of aluminum alloys. In order to attain the beneficial working mechanism of local hardening, the fundamental behavior between strength and formability has to be kept in mind. In this context, only these part zones are to hardened showing a low stretching.

3. Process window for short-term hardening

In light of the importance of the hardenable aluminum alloys of the 6000-series for the automotive industry, the present work deals with the alloy AA6181PX close to series production. The ending “PX” designates the fast-hardenable characteristic of the alloy. Heat input has different influences on the mechanical behavior of fast-hardenable aluminum alloys of the 6000-series [1]. In order to achieve the set goal with a defined increase of the strength, the influence of the different heat treatment parameters have to be studied first. In this context, the temperature-time-profile, which includes the heating rate, maximum temperature, holding time on a specific temperature, cooling rate, and the cooling time were the influencing parameters to respect. In this study, the cooling rate was constant. No additional cooling device was applied. In this context, the heating rate was higher than 50 K/s.

The studied parameters were the maximum temperature T_{max} and holding time t_{hold}. In accordance to [2] a full factorial design of experiments was set up. The range of the maximum temperature T_{max} reached from 50 to 400 °C and of the holding time t_{hold} from 1 to 1200 s (Table 1). The long holding time at a specific temperature was ensured using a power control of the energy output. Furthermore, a graphit layer was applied on the specimen surface assuring a homogenous absorption of the laser radiation. In order to characterize the plastic behavior of the heat treated alloy, tensile tests according to DIN EN ISO 6892-1 [3] were performed. For each parameter combination, six specimens were tested. An optical strain measurement system was utilized due to the high resolution of the cameras. In order to achieve a fundamental understanding of the macroscopic hardening effect, differential-thermal-analysis (DTA) according to DIN 51007 [4] was applied.

Table 1. Parameters for the heat treatment

Parameter	Absolute value										
Maximum temperature T_{max}, °C	RT	50	100	150	200	225	250	300	350	400	--
Holding time t_{hold}, s	1	15	30	60	120	180	300	600	800	1000	1200

In dependency of the part geometry and therefore the critical zones, different layouts have to be considered. By using the laser radiation, the flexibility of the irradiation is very high. Furthermore, the high specific cooling rate of the laser via self-quenching renders an extra cooling system unnecessary. The modifying and adoption of the required material properties can be guaranteed by the high energy density and pulse duration of the radiation. Moreover, the material properties distribution can be set precisely up to 5 mm between heat treated and not treated area using laser as heat treatment tool [5].

For the definition of a process window, several process requirements are necessary. The first one represents the yield strength (YS). As a characteristic for the onset of plastic deformation, the YS and its behavior after a heat treatment are shown in Fig. 2 a. The increase of the YS above 182 MPa, which signifies the value of the as-received, natural aged initial T4 material condition, is restrained by the maximum temperature. For the range $1 \leq t_{hold} \leq 1200$ s the YS decreases for a maximum temperature $T_{max} > 275$ °C. An increase of the YS is given for the maximum heat treatment temperature below 275 °C. Within the range of 150 °C $\leq T_{max} \leq$ 275 °C and of 1 s $< t_{hold} \leq$ 1200 s the YS can be enhanced up to 50 % compared to its as-received condition. This maximum hardening potential is specified for a constant maximum temperature of 225 °C and a holding time of at least 800 s and more. Similar to the artificial aging process [6] the hardening of the aluminum alloy rises with longer holding time (Fig. 2 a). The same effect is perceived during the artificial ageing of fast-hardenable aluminum alloys.

In order to understand the fundamental hardening mechanism of the fast-hardenable aluminum alloy AA6181PX, a differential-thermal-analysis (DTA) was performed. The specimen was first heat treated and then analyzed. In this context, four parameter combinations were selected for the DTA, whereas three tests were applied for each parameter combination. The maximum temperatures for the pre-heat treatment were 150, 200, 250, and 300 °C for a constant holding time of 120 s (Fig. 2 b). The results of the DTA investigation show that the strength enhancement is based on the precipitation of the alloyed elements (Mg, Si). In accordance to Edwards et al. [7] the existence of needle and rod-shaped like β'' and β' precipitates in the scale of few nanometers was proven. These semi- and incoherent precipitates set a higher resistance against the dislocation movements. More energy is required for the plastification of the material, which results in an increase of the material strength.

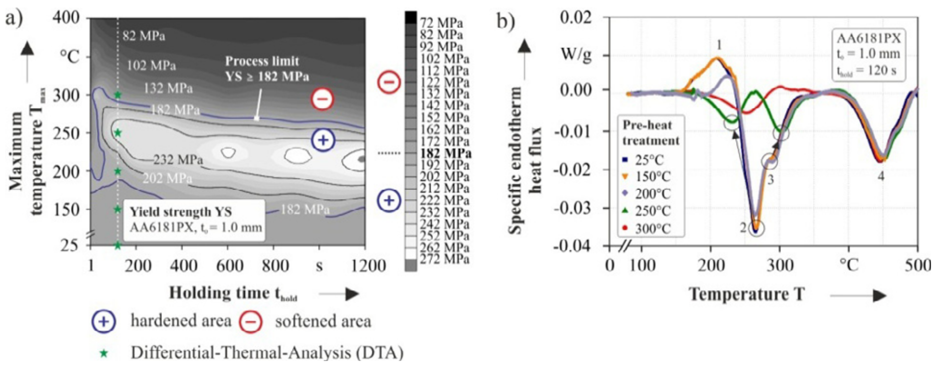

Fig. 2. (a) heat treatment process window with respect to the onset of yielding (YS ≥ 182 MPa) of the aluminum alloy AA6181PX; (b) differential-Thermal-Analysis (DTA) results of the preceded heat treated aluminum alloys AA6181PX

Regarding the peaks of the curve with a pre-heat treatment at 150 °C and without heat treatment – here designated at room temperature at 25 °C – no significant differences can be observed (Fig. 2 b). At the peak 1 the coherent MgSi-clusters, which aroused during the natural ageing, are dissolved. The endotherm peak at a process temperature of 200 °C shows the required energy. Similar to [7], the diffusion less formation of the semi- and incoherent β" and β' precipitations exists at nearly 260 (peak 2) and 280 °C (peak 3). Compared with Dutta and Allen [8] the stable equilibrium β-phase (Mg_2Si) is formed at 450 °C (peak 4). With a pre-heat treatment above 200 °C the peak of the formation of β" and β' is shifted. The transition of the solved MgSi-cluster into β" precipitates (peak 2) declines to lower temperature, whereas the formation of β' (peak 3) increases to higher temperature. In comparison to the curve at 25 or 150 °C, the low tip indices the amount of the formed precipitates. Therefore, fewer precipitations were formed for during the DTA, but during the pre-heat treatment. With higher maximum temperature of the pre-heat treatment, e. g. T_{max} = 300 °C, the peak and the tip of the curve, which indicates the formation of the hardening β" and β' precipitates, declines more and more. The reason is given by the drop of number of nucleation for the formation of the precipitates [9].

According to OEM standards [10], the minimum ultimate elongation (UE) must not exceed 12 %. Hereby, the ultimate elongation represents the second limit of process window. Considering the results of the tensile tests (Fig. 3 a), two sectors of the process window are eligible for the heat treatment, in order to fulfill the minimum requirement of 12 % ultimate elongation. Thereby, the maximum temperature T_{max} holds the key influence. T_{max} must not either exceed 250 °C or has to exceed the 400 °C mark. Between 250 until 400 °C the formability of the aluminum alloy sinks significantly. The reason for this decrease remains in the forming of hardening semi- and incoherent precipitates (β" and β') during the heat input, which hinder the dislocation movements and therefore reduce the formability of the material. A look at the holding time t_{hold} shows a slight decrease of the formability with increasing t_{hold}. This reduction is observed for a maximum temperature T_{max} below 250 °C. For T_{max} > 400 °C the inverse effect is achieved instead. With increasing holding time and a maximum temperature above 400 °C the ultimate elongation increases due to dissolution of the hardening precipitates (Fig. 3 a).

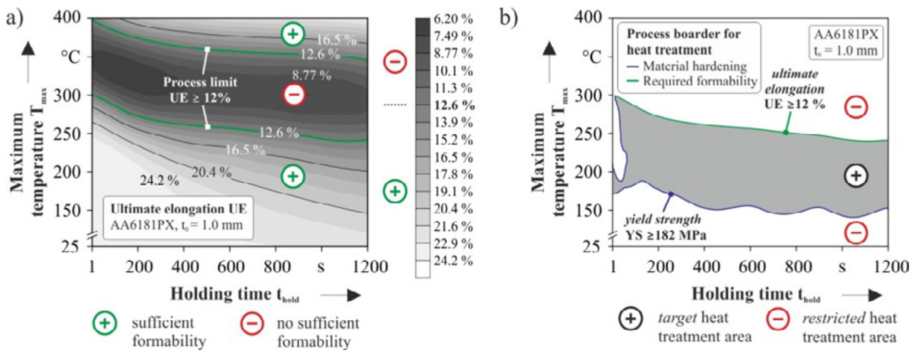

Fig. 3. (a) heat treatment process window with respect to the required formability (UE ≥ 12 %) of the aluminum alloys AA6181PX; (b) heat treatment process window with respect of two material parameters - the material hardening (YS ≥ 182 MPa) and the formability (UE ≥ 12 %)

In order to obtain the required material properties, which are optimized to the forming operation, the strength and the elongation of the aluminum alloy have to be respected. Due to the inverse effect of these two key parameters an overall process window has to be identified, which fulfills the two essential requirements best. In this context, a combined process window for the heat treatment (Fig. 3 b) is maintained by overlapping of the two process windows for hardening and ultimate elongation. The border to higher heat treatment temperature is given by the ultimate elongation, which has not to exceed the 12 %. The lower border is given by the hardening requirement, where the yield strength has at least 182 MPa. For 150 °C ≤ T_{max} ≤ 250 °C and 50 s ≤ t_{hold} ≤ 1200 s this overall process window is in comparison to the specific one for hardening or formability significantly reduced. In dependency of an additional parameter, for example the process time, this combined window for the heat treatment shrinks furthermore. Biggest advantage of this window is a fast and precise definition of the needed heat treatment parameters to maintain the required material properties (Fig. 3 b).

4. Hardening layouts for Tailored Heat Treated Blanks

Based on the hardening effects, the benefit of a local hardening of THTB for the forming operation is considered in the following via Finite-Element-Analysis (FEA) using the commercial software program AutoformPlus R3. In context of modeling the plastic behavior of the aluminum alloy, the flow curve model of Hockett-Sherby was applied showing the best approximation of the hardening forming behavior of aluminum alloys [11]. In order to identify the properties distribution of the sheet metal and to evaluate the heat treatment for the enhancement of the forming limit of fast-hardenable aluminum alloys, a demonstrator part with a complex geometry, which provides all relevant strain states of a typical part, was required. Hereby, the cross die geometry was selected as model experiment. Due to its concave and convex contour the cross die shows all relevant strain states like plain strain, biaxial stretching, compression-tension, and uniaxial tension. For the forming process the deep drawing was set up as forming operation (Fig. 4 a).

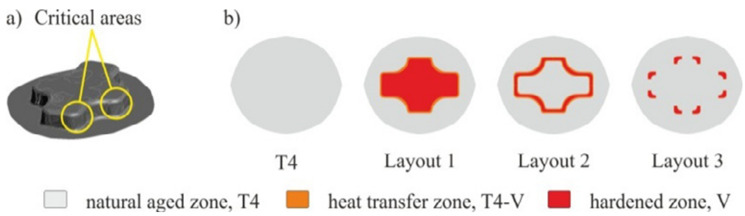

Fig. 4. (a) cross die geometry as model for deep drawing; (b) heat treatment layouts of the initial blank

In order to identify the optimal properties distribution of the THTB, different heat treatment layouts were studied. In this context, the heat treatment layouts were varied (Fig. 4 b). The first layout focuses on the force transmitting, in which the whole part bottom is hardened with the goal to increase the force induction from the punch into the blank. The second strain-oriented layout respects the potential of elongation of the bottom area, which can be applied to increase the material flow into the critical area. The third layout focuses on the critical radius section, where the occurring plain strain causes a local thinning and cracking of the material. These heat treatment layouts were qualified via forming limit curve at a deep drawing depth z_{max} of 60 mm of the cross die.

In context of designing the hardening layouts for THTB, the strain state holds an important role. According to the forming limit curve, the plain strain state ($\varphi_2 = 0$) shows the lowest formability (Fig. 5). This is the area providing an early thinning and an elevated risk of failure by crack. The idea is to enhance the material flow from the forming zone into these critical plain strain zones to delay to the thinning to higher forming ratio. In this context, an early plastification of the forming zone and, therefore, an enhanced force transfer from the punch over the bottom and the wall into the flange are required.

Layout 1 shows the realization of this idea. Hereby, only the bottom zone of the part is hardened. Fig. 5 shows the positive effect on the formability of the aluminum alloy AA6181PX. According to the above presented second working principle of local hardening, the formability of the fast-hardenable aluminum alloy increased visibly. The maximum drawing depth of 30 mm of conventional blank raised about 100 % to 60 mm drawing depth for layout 1. Regarding the plain strain state of the part and its distance to the heat-treated forming limit curve (FLC), the major strain φ_1 declined about 0.03. In order to reduce the risk of cracks and therefore to decrease the plain strain elongation, only the contact area between blank and punch radius is hardened in layout 2. The strain-oriented layout 2 reached a similar maximum drawing depth z_{max} of 60 mm. The essential major strain φ1 of the layout 2 at the plain strain condition sank about $\Delta\varphi_1 = 0.15$ to the critical heat-treated FLC (Fig. 5). A further forming of the blank is feasible before the same critical plain strain state is reached. Compared to layout 1 a small material plastification close to the radius, i.e. the transition area between bottom and the wall, could be achieved allowing a reduced plain strain elongation of the material showing an increased distance to heat-treated FLC of 0.15. With the scope to decrease the plain strain plastification furthermore and to reduce the area to be heat treated, only the critical area of the blank was hardened in layout 3. Compared to layout 1 and 2 the layout 3 achieved similar results for the formability. A maximum drawing depth z_{max} of 59 mm was accomplished. The improvement of the formability was about 100 % to the conventional blank. The plain strain plastification, moreover, declined. Hereby, the major strain for the critical plain strain path felt about $\Delta\varphi_1 = 0.2$ (Fig. 5).

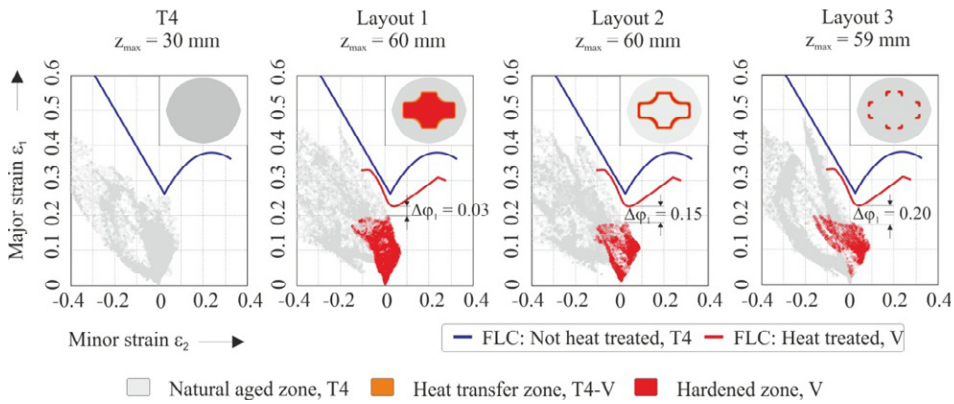

Fig. 5. FLC and strain-paths of a cross die geometry with different THTB layouts of the aluminum alloy AA6181PX

Summed up, the local hardening represents one promising option to enhance the forming limit of fast-hardenable aluminum alloys. The application of local hardening is only given for critical blank zones showing low or nearly no elongation. The plain strain elongation of the sheet metal declines and the risk of failure sinks for the same forming ratio like for z_{max} = 30 mm. The result is either a reduced risk of fracture for the same deep drawing path or a higher deep drawing depth for the same risk of fracture. Both effects mean an increase of the forming limit of fast-hardenable aluminum alloys.

5. Conclusion and Outlook

Tailored Heat Treated Blanks have great potential to enhance the forming limit of fast-hardenable aluminum alloys. In the context of modifying and adapting the material properties to the forming operation by a local heat treatment, this paper dealt with the enhancement of the material strength, the hardening. First, the two hardening mechanisms are presented showing how failures like wrinkling and crack can be avoided by a local material hardening. Second, a process window of the heat treatment was defined for two requirements, the yield strength and ultimate elongation, allowing an optimal modifying of the material properties. In the last part, FEA based results of the optimal properties distribution are shown. Hereby, different layouts are considered proving the applicability of local hardening for enhancement of the formability of fast hardenable aluminum alloys.

Future investigations will focus on the application potential of local hardening in conditions near to series production. The influence of local hardening on friction and on the process time needs to be characterized due to the higher demands of series production and the economic efficiencies. An additional aspect would be the combination of softening and hardening for the enhanced application of THTB in the automotive industry.

Acknowledgements

The authors would like to thank the German Research Foundation (DFG) for the financial support. Another word of thank goes to the School of Advanced Optical Technologies (SAOT) and the Cluster of Excellence of Engineering of Advanced Materials (EAM) for their support.

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